925

REPAIR AND CALIBRATION
OF
AIRPLANE INSTRUMENTS

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The following publication, entitled "Repair and Calibration of Airplane Instruments," is published for the information and guidance of all concerned.

[062.11, A. G. O.]

BY ORDER OF THE SECRETARY OF WAR:

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REPAIR AND CALIBRATION OF INSTRUMENTS.

I. GENERAL CONSIDERATIONS.

The life of airplane instruments can not be expected to be long, because of the great vibration and shocks to which they are subjected, but they will give better and longer service if given proper attention. Every airdrome should have one, or more as the necessity demands, instrument mechanician or repairman specially trained for the work to look after the cleaning, repair, and calibration of instruments.

Certain instruments should be cleaned and oiled at regular intervals; the tachometer at least once in three months, and the watches or clocks once in six months. In the other instruments the parts have slow motion, so there is little or no wearing and the cases are tight enough to keep out dust and dirt. Consequently, barring accidents these instruments should not require much attention. However, one source of trouble that frequently occurs is the loosening of a screw or part due to vibration. Such a difficulty is simple to repair, but until repaired renders the instrument useless.

The air pressure, gasoline pressure and oil pressure gages, and airspeed indicator may be injured by an overpressure, which results in a permanent "set" of the Bourdon tube or the aneroids. At least the calibration will be changed, and the readings of the instrument should be checked by comparison with a standard or the readings of a manometer as described later. If the errors are not large the instrument still can be used if the necessary corrections are applied to the readings; but if the errors are large the instrument should probably be replaced by a new one, since satisfactory repairing would require new parts.

The radiator thermometers can not be repaired if the bulb, tubing or Bourdon tube develop any trouble, for then the instrument must be refilled, and this requires special equipment and the liquid for which the thermometer was designed. If the trouble is in the sector gear, pinion, or hairspring then the repairing can be readily done.

II. EQUIPMENT OF SHOP.

The instrument repair shop should be equipped with the necessary tools and apparatus for testing and calibrating instruments. The former include a jeweler's lathe and accessories, and small bench tools.

(See Appendix for list of tools.) Since all instruments have been subjected to the tests required by the specifications before they are accepted, new instruments are probably correct within the limits allowed. But after considerable use under severe service conditions the calibration of an instrument may change to such an extent that the readings indicated are quite misleading. In order to check up used instruments and avoid misinformation from unreliable instruments every airdrome should have the necessary apparatus for calibrating all instruments. For complete tests, involving effects of temperature, vibration, overpressure, etc., instruments should be sent to the Bureau of Standards, where complete apparatus is available for this work. A good plan to be followed is to send to the Bureau of Standards two sets of the following instruments to be calibrated, and to keep these exclusively as standards with which to compare other instruments; (1) air-pressure gage, (2) oil-pressure gage, (3) tachometer, (4) altimeter, (5) air-speed indicator. With two instruments the readings of one may be checked by the other. Wherever a large number of instruments are to be tested and considerable accuracy is desired an absolute method of calibration should be employed as described below.

III. METHODS OF CALIBRATION.

1. Air-Pressure Gage.

The scales of the air-pressure and gasoline-pressure gages are marked in pounds per square inch. The most accurate and convenient method of measuring a hydrostatic pressure is with a liquid open arm manometer. The pressure between the two levels of liquid is given by the following equation,

$$p=hd. \tag{1}$$

The pressure p will be in pounds per square inch when the head, or difference in level, h is expressed in inches and the density d in pounds per cubic inch. The liquid used should have such a density that the range of h will be large enough for accurate readings and small enough for convenience. Mercury is the best liquid for a pressure of a range from 0 to 10 pounds such as the air-pressure gages have. The density of mercury at room temperature, 20° C, is 0.488 pounds per square inch. Hence equation (1) becomes

$$p=0.488\ h. \tag{2}$$

Figure I is a diagram of the necessary apparatus for testing air-pressure or gasoline pressure gages. The manometer is made of ¼-inch o. d. glass tubing of rather heavy wall. The rest of the tubing is of copper or brass. The manometer should be thoroughly cleaned and clean mercury used. It should be filled to within two inches of the bend at the top of the left hand tube. The scale may

be marked off in inches of height with the zero at the bottom, or in pounds of pressure with the zero at the level of the two columns

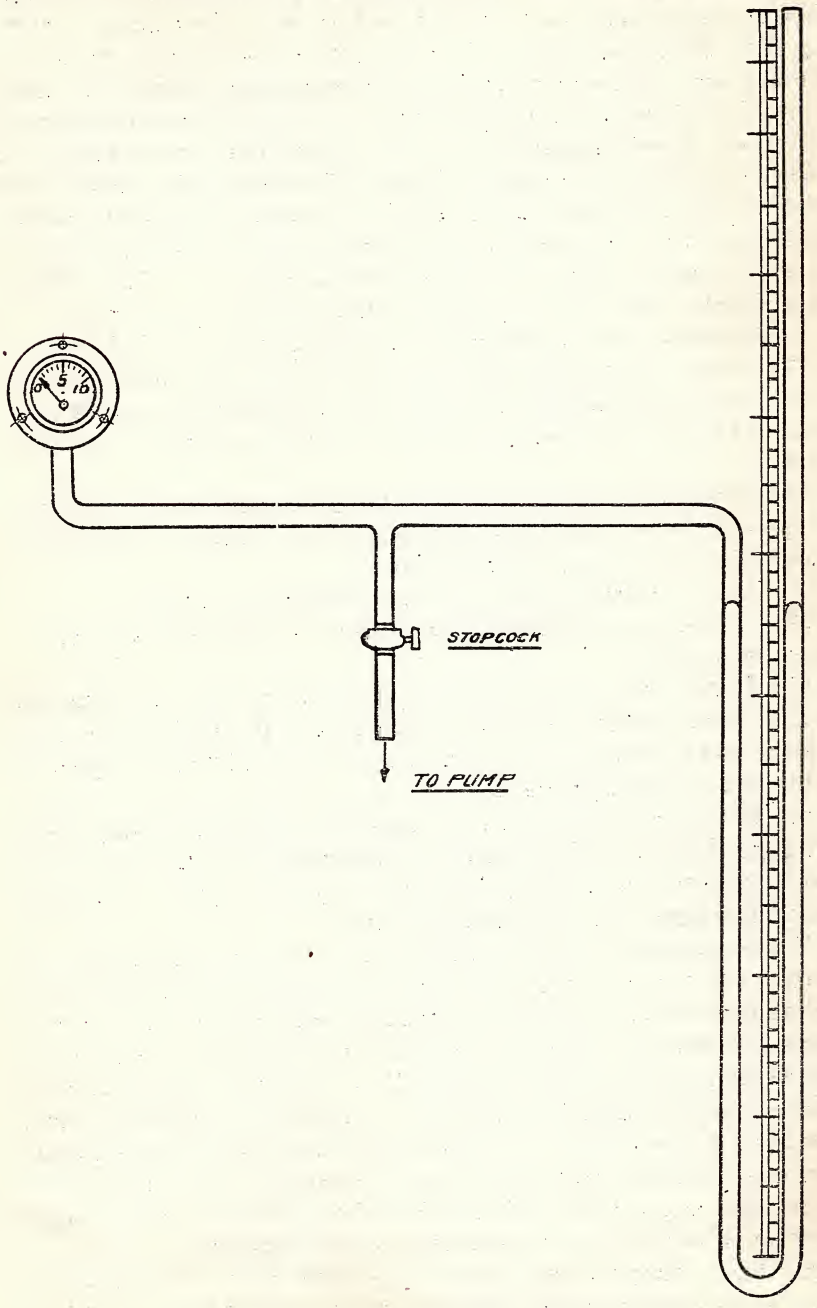

FIG. 1.—AIR-PRESSURE GAGE TESTING APPARATUS.

when no pressure is applied. If the latter plan is used care must be taken to see that the zero line is at the level of the mercury columns

every time before a test is made. With the scale in inches the position of the tops of the mercury columns is immaterial so long as they are level, since the height of each is read. In making a reading care should be taken to have the eye on level with the top of the meniscus (the convex surface of the mercury column) in order to avoid parallax, and the height of the very tip of the meniscus should be taken. A scale marked on a mirror placed back of the tubes, or a slide with a horizontal edge in front of the tubes and a mirror back of the tubes furnish accurate means of reading the height of the meniscus. The pump used is an ordinary hand compressor such as is used in the air pressure system of an airplane. There should be a stopcock between the pump and the rest of the apparatus.

The procedure to be followed in calibration is as follows:

(1) Screw the gage in place and test for leak by pumping up a little pressure, closing the stopcock and watching the mercury columns. If they hold steady, go ahead, otherwise find the leak and close it.

(2) Pump up enough pressure so the gage reads exactly one, tapping the gage so as to avoid sticking of the pointer, then read the manometer, and record the readings.

(3) In this manner go up the scale, 1 pound at a time.

(4) If desired, readings may be taken coming down the scale, 1 pound at a time.

(5) If the scale is in inches the pressure is then computed for each pressure tested by using equation (2). If readings are taken coming down the scale, the mean of the "up" and "down" pressure is taken as the true pressure.

(6) If there is an error of more than 0.3 of a pound at any points, the gage should be rejected and another tried; or if the error is not too large a card indicating the errors may be prepared and posted beside the gage on the instrument board.

If the manometer is not available, and two instruments, the calibration of which is known (i. e., made at the Bureau of Standards), are at hand, the questionable instrument can be calibrated by comparison with these. For this method three couplings or unions connected in parallel to the tubing will be necessary. The procedure then is similar to that described above. Readings of all three instruments are taken at each pressure, and the readings of the standards corrected from the calibration curves furnished. The errors of the instrument being calibrated are then determined by comparing its readings with the *corrected* readings of the standards.

A "Dead-Weight Gage Tester" described in the next paragraph may be used for testing air pressure gages, but is not as accurate for pressure gages of low range as either of the methods described above.

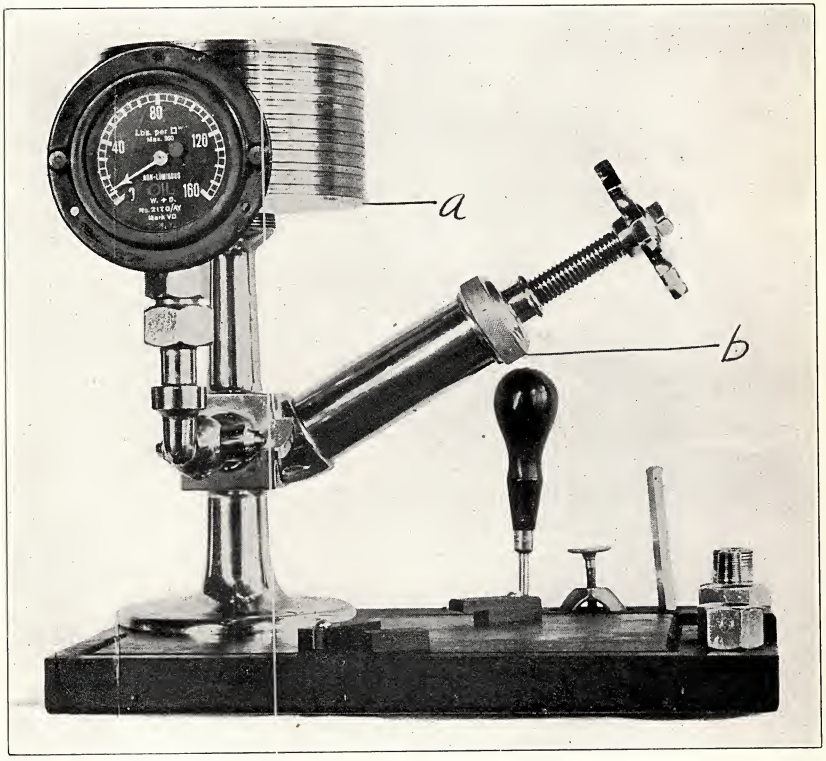

FIG. II.—DEAD-WEIGHT GAGE TESTER.

2. Oil Pressure Gage.

For testing oil pressure gages a mercury manometer is not practical because of the great length necessary, more than 20 feet. The Dead-Weight Gage Tester is the most practical instrument for testing large range gages. Such an instrument is shown in Figure II. The principle involved is that of the hydraulic press. The platform *a* is carried on a piston which is ground to a perfect fit in the cylinder. The cylinder, connecting pipes and pump *b* are filled with oil. Weights are placed on the platform and pressure applied by the pump until the piston is pushed up and rests alone on the oil. The pressure on the oil and consequently the gage is proportional to the total weight on the piston. The piston is generally made with a small cross section, say one-fourth square inch, then the pressure per square inch is four times the weight on the piston. Hence for calibrating an oil-pressure gage of range 0 to 120 pounds per square inch, the weights used should total 30 pounds.

Readings should be taken at steps of 10 pounds and may be taken going "up" and coming "down." The gage should be discarded if there is an error of more than 3 pounds at any point.

If a gage tester is not available and two standard oil pressure gages are, the same method and the same apparatus may be used as described for air pressure gages. Of course the construction of the apparatus, including unions and stopcock, should be heavy enough to stand the necessary pressure.

3. Gasoline Level Gage.

The only way this instrument can be calibrated is by installing in the tank in which it is to be used, and then measure the gasoline as poured in and read the gage. Since the purpose of the gage is to indicate the amount of gasoline *left* as the supply is used, and since the gage may stick as the float goes down, the tank should be drained and the readings of the gage noted as measured quantities are taken out. This is more important than to take readings as the tank is being filled.

4. Thermometer.

The apparatus necessary for testing the radiator thermometers consists of (1) a reliable chemical mercury-in-glass thermometer of range 0 to 110° C., which should be kept as standard and (2) a container in which water may be heated. The procedure is as follows:

(1) Fill the container with pure water; place the bulb of the radiator thermometer so it is entirely submerged but none of the capillary tubing is in the water; place the indicator head in such a position that it may be read conveniently, but so neither it nor the capillary tubing is heated by the source of heat for the water.

(2) Place the standard thermometer in the water so it is immersed up to the point of the scale to be read.

(3) The water should be heated up gradually, being stirred well all the time to insure uniform temperature, and the readings taken every 10°.

In calibrating under the above conditions the error at any point should not be greater than 3° for any type. Of course if the "standard" has any errors the necessary corrections should be applied before the errors of the instrument being calibrated are computed.

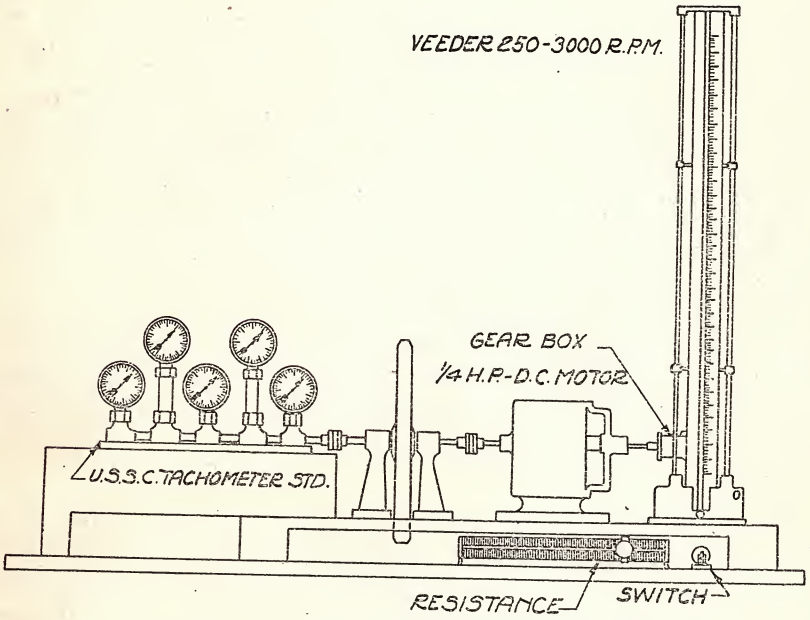

FIG. III.—TACHOMETER TESTING APPARATUS.

5. Tachometers.

Apparatus for testing tachometers is perhaps the most important of any. Figure III shows in diagram the apparatus used at the Bureau of Standards for room temperature testing. The power plant is a one-quarter horsepower direct-current motor. Just to the right of the motor is a Veeder liquid tachometer coupled to the motor shaft; at the left is a heavy flywheel which keeps the motion steady, and at the extreme left a set of gear boxes, on which five tachometers can be mounted at the same time and driven at the motor speed. The Veeder tachometer is the standard, the revolutions per minute being measured by the height of a column of liquid which is pushed up by the pressure of the liquid in a centrifugal pump at the base of the instrument and driven by the motor.

While the complete apparatus is desirable it is not necessary, especially where only a few instruments are to be tested. The es-

sential parts are the motor, flywheel, and at least three gear boxes. The Van Sicklen tachometer is a very reliable instrument. Consequently if two such instruments, calibrated by the Bureau of Standards, are mounted on the gear boxes with the instrument which is being tested, a very good check can be made. Of course corrections taken from the calibration curves should be applied to the readings of the standards. A simple method of checking a tachometer is by a revolution counter and stop watch. The revolution counter should be well mounted so there is no slipping between it and the motor shaft. Such an instrument made by the Veeder Co. is very satisfactory and inexpensive.

In using either the standard tachometer or the counter and stopwatch several readings should be taken at each speed. The flywheel is quite essential to maintain a constant speed while this is being done. The motor should be shunt wound, and a rheostat furnished which may be put in series with either the armature or field by a double-throw switch. With such an arrangement a wide variation in speed may be obtained. If direct current is not available so an alternating-current motor is necessary some other method must be used for varying the speed. The best is a friction-wheel drive. A heavy wheel should be used so as to serve both as a balance wheel and as a part of the drive.

The lowest speed which can be kept constant is about 600 revolutions per minute. The procedure to be followed in taking readings is somewhat different for the chronometric from what it is with the centrifugal. That for the chronometric will be given first.

(1) Adjust the motor to the lowest constant speed. Two persons are required to take the readings, one to read the standard, of whatever form is used, the other to read the instrument being tested. Readings should be taken at the same instant and repeated at least five times for each speed.

(2) Speed up the motor 200 revolutions per minute more and again read the instruments. Proceed in this manner at 200 revolutions per minute intervals throughout the range.

(3) With the centrifugal tachometer regulate the motor so that the speed increases about 200 revolutions per minute in 20 seconds; take instantaneous readings when the standard indicates the desired speed. As with the chronometric, readings should be taken at intervals of 200 revolutions per minute. Then in a similar manner decrease the speed uniformly and take readings. The difference between the "up" and "down" readings is called the lag. The "down" readings are generally higher.

(4) The process of (3) should be repeated five times and the average taken.

6. Altimeters.

The simplest method of testing an altimeter is by comparing it with standard instruments. For this a glass container, or glass-covered container, is necessary and some sort of an air pump for exhausting it. The usual container consists of a metal base plate with the upper surface ground flat and an opening to the pipe leading to the pump, and a glass bell jar with the edge ground so as to make an air-tight joint with the plate. The use of a heavy grease at the joint aids in making it air-tight. The pump may be a small hand pump, similar to a hand compressor, but with the valves reversed; but where considerable testing is to be done, a power-driven pump is desirable, such as the rotary oil-sealed pump made by the Central Scientific Co., Chicago. An auxiliary vacuum tank will make a more uniform rate of exhaustion possible.

Where accurate and reliable calibration is desired, either a mercury manometer, or a mercury barometer with the well inclosed, except for a tube to the vacuum chamber, is necessary. The latter is the more convenient instrument. The scale may be either in inches of mercury pressure, in which case an altitude-pressure table is required to find the altitudes corresponding to the pressures read, or the scale may be in feet of altitude. Figure IV shows such a barometer and the bell-jar container.

The procedure of the testing given below is taken from the specifications for altimeters, No. 27,058–A, and includes what is known as the "Calibration Test" and "Lag Test." These two are sufficient to determine whether or not an instrument is serviceable.

(1) Read the barometer when open to the air, and by referring to Table I, if necessary, determine the corresponding altitude and set the instruments to be tested at this altitude. Then place in the bell-jar vacuum chamber and reduce the pressure at a rate corresponding to an increase in altitude of 1,000 feet in three minutes. A one-minute rest, following the decrease in pressure, is given the instruments, the vacuum chamber is jarred to prevent sticking of the pointers, and the reading taken. (If "standard" altimeters are used instead of a mercurial barometer, all instruments should be set with the zero under the pointer, and of course the proper corrections taken from the calibration curves applied to the readings of the standard instruments.) The error of each reading should not exceed the value given in Table II. The motion of the pointer should be free from jerks.

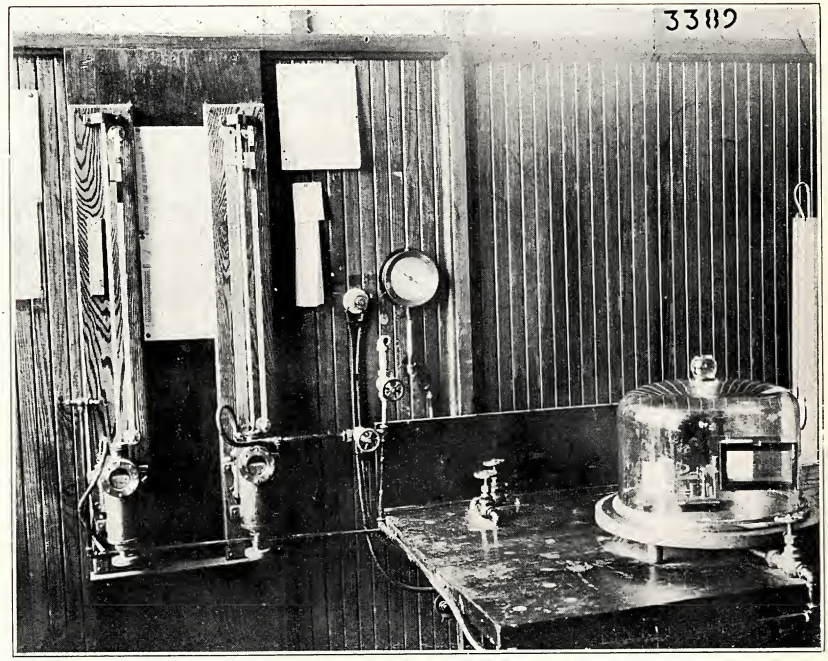

FIG. IV.—ALTIMETER TESTING APPARATUS.

(2) When the pressure corresponding to the upper limit of the scale has been reached, let in air so the pressure decreases at a rate corresponding to 1,000 feet of altitude in three minutes. After a one-minute rest period, jar the container and read the instruments. The readings so taken should not differ from those taken on "going up" by more than 1 per cent of the total range of the scale. Five minutes after the vacuum chamber attains normal pressure, after tapping the bell-jar, the pointer should not deviate from the original setting by more than 1 per cent of the total range of the scale.

The following tables give the altitudes corresponding to the various pressures and the permissible errors at various altitudes.

TABLE I.—*Altitude pressure table.*

Computed from the following equation for a temperature of 10° C. and the corresponding mean humidity,

$$H = 62900 \log_{10} \frac{29.9^1}{P}$$

where H=altitude in feet.
P=barometric pressure in inches of mercury.

P. mm.	P. inches.	H. feet.	P. mm.	P. inches.	H. feet.
759.6	29.90	0	378.9	14.91	19,000
732.4	28.83	1,000	365.3	14.38	20,000
706.0	27.79	2,000	352.2	13.86	21,000
680.6	26.79	3,000	339.5	13.36	22,000
656.2	25.83	4,000	327.3	12.88	23,000
632.6	24.90	5,000	315.5	12.42	24,000
609.8	24.00	6,000	304.2	11.97	25,000
587.8	23.14	7,000	293.2	11.54	26,000
566.8	22.31	8,000	282.7	11.13	27,000
546.4	21.51	9,000	272.5	10.73	28,000
526.8	20.73	10,000	262.8	10.34	29,000
507.8	19.99	11,000	253.3	9.97	30,000
489.6	19.27	12,000	.....	.....	.....
472.0	18.58	13,000	.....	.....	.....
455.0	17.91	14,000	.....	.....	.....
438.6	17.26	15,000	.....	.....	.....
422.8	16.64	16,000	.....	.....	.....
407.6	16.01	17,000	.....	.....	.....
393.0	15.47	18,000	.....	.....	.....

[1] This table is taken from the Bureau of Standards Altitude-Pressure Tables, which is computed from the constants given in the Smithsonian Meteorological Tables No. 20. All the altimeters put into production during the war and accepted by the Air Service are calibrated from this table. It should be noted that this does not agree with the table of "Standard Air" used by the Flight Test Department, Engineering Division. (See Information Circular No. 80.) The apparent discrepancy should cause no difficulty if understood. For both tables the equations used for computation are empirical, and each will give the correct altitude if the proper temperature corrections are applied; but of course these are different for the two tables and should not be confused. The proper corrections for altimeters calibrated by the above table are given in the pamphlet "Altimeters for Aerial Navigation."

TABLE II.—*Permissible error table.*

Height.	Permissible error.	Height.	Permissible error.
Feet.	*Feet.*	*Feet.*	*Feet.*
0	50	16,000	300
1,000	50	17,000	300
2,000	50	18,000	300
3,000	50	19,000	350
4,000	50	20,000	350
5,000	100	21,000	400
6,000	100	22,000	400
7,000	100	23,000	400
8,000	150	24,000	500
9,000	150	25,000	500
10,000	200	26,000	500
11,000	200	27,000	500
12,000	200	28,000	600
13,000	250	29,000	600
14,000	250	30,000	600
15,000	250		

7. Airspeed Meters.

The airspeed meter may be calibrated by placing the pressure head, either Venturi-Pitot, or Pitot, in a wind tunnel, connecting with the indicator, and comparing the readings with the airspeed of the tunnel as given by a standard laboratory Pitot. Of course apparatus for such a test is not available at most airdromes, and is not needed. The pressure heads have all been tested before accepted and distributed to supply depots, and their accuracy will not change unless damaged or the openings are clogged with dust, water, oil, etc. So if the pressure heads are kept clean and in good condition there is no need for calibration. However, the indicators are not so durable and it is advisable to check them up occasionally. This may be done in either of two ways; (1) by connecting the suction tube in parallel with the suction tube of a standard indicator, the errors of which are known, and applying suction to the two corresponding to the various airspeeds for which calibration is desired; or (2) by connecting the suction tube to a water manometer and comparing the indicator readings with the manometer. In either method the pressure tubes and pressure might be used in place of suction, but the latter is easier to manipulate and with it there is less chance of letting moisture into the indicators.

The apparatus to be used with the second method is shown in Figure VI, and the relation between the airspeed and pressure shown by the curve of Figure V and Table III, which apply to the Venturi-Pitot airspeed meter. As pointed out in the pamphlet "Airspeed Meters for Aerial Navigation" the equation for pressure of the Venturi-Pitot is:

$$V = 17.88\sqrt{h}$$

where V is the airspeed in m. p. h. and h is the pressure in inches of water. If the values of V are plotted against h on ordinary coordi-

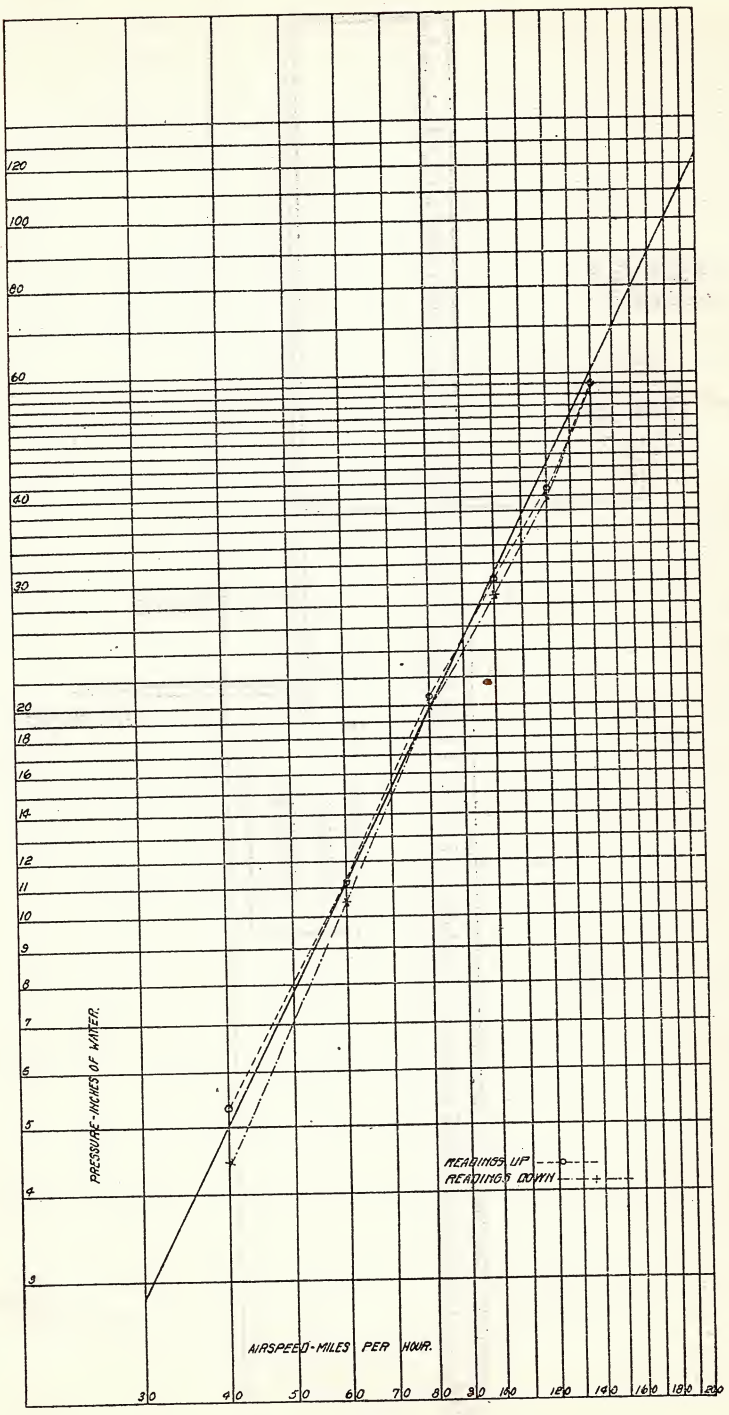
120
100
80
60
40
30
20
18
16
14
12
11
10
9
8
7
6
5
4
3
PRESSURE-INCHES OF WATER.
READINGS UP
READINGS DOWN
AIRSPEED-MILES PER HOUR.
30
40
50
60
70
80
90
100
120
140
160
180
200

FIG. V.

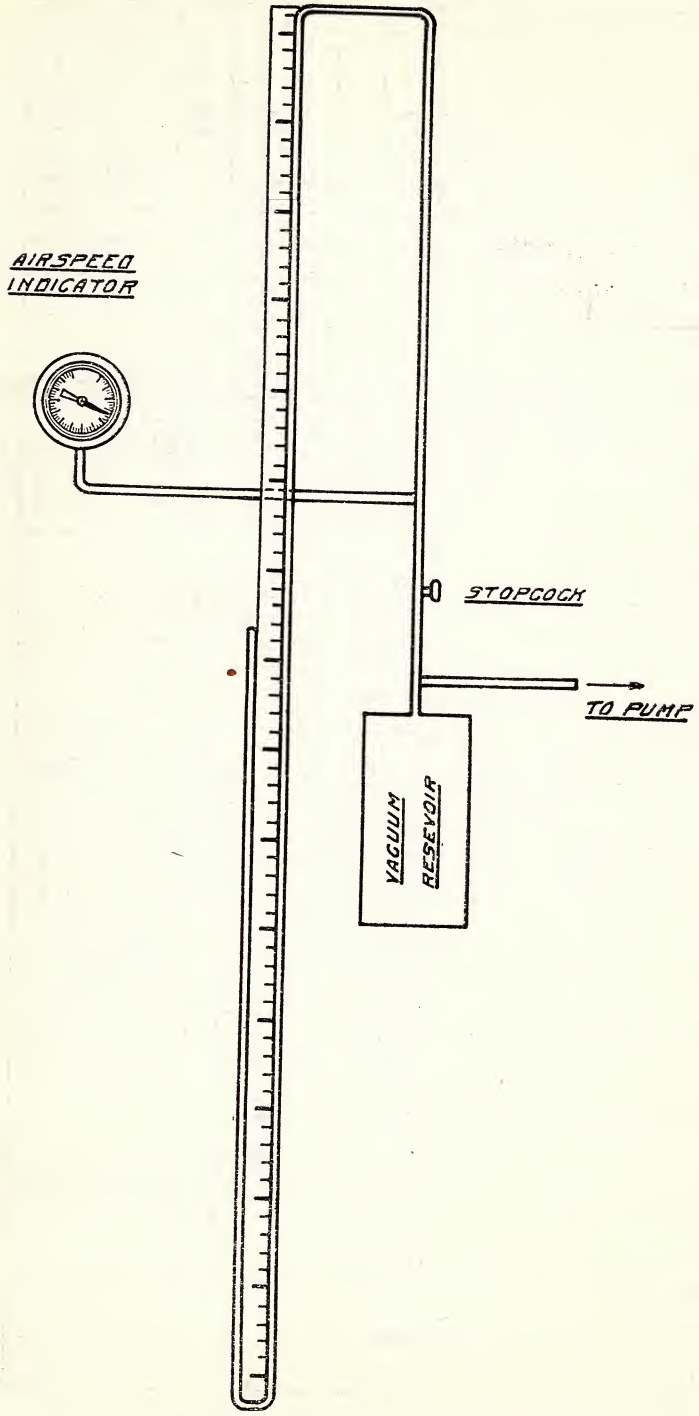

FIG. VI.—AIRSPEED INDICATOR TESTING APPARATUS.

nate paper the curve is a parabola. By using double logarithmic paper a straight line is obtained which is more convenient.

TABLE III.—*Airspeed-pressure table for Venturi-Pilot airspeed meter.*

Computed from $V = 17.88\sqrt{h}$

V.	h.
0	0
30	2.81
40	5.00
50	7.81
60	11.24
70	15.30
80	20.00
90	25.30
100	31.24
110	37.80
120	45.00
130	52.80
140	61.20
150	70.27
160	80.00

As is apparent from the table the manometer must be over 80 inches in height in order to calibrate an instrument over the full range of the scale 0 to 160 m. p. h. The manometer should be of glass tubing $\frac{1}{2}$-inch o. d., and for connections to the pump, indicator, etc., metal or rubber tubing may be used. The vacuum chamber makes posible the application of an uniform suction. The pump may be either a hand vacuum pump or small power pump as described for the testing apparatus of altimeters. There should be a stopcock between the pump and vacuum chamber; and the stopcock between the vacuum chamber and manometer should be capable of a very fine adjustment so a *very* slow flow of air may be obtained. The manometer should be filled with pure water so that the level is a little more than 40 inches in each arm. The scale is graduated in inches with $\frac{1}{10}$-inch subdivisions. Since the manometer can be read with a greater accuracy than the indicator the better plan is to reduce the pressure in the manometer and indicator until the pointer stands exactly at some division mark of the scale and then read the manometer. Since the indicator is seldom used below 40 m. p. h. the first reading may be made at this point.

Below is given the procedure to be followed:

(1) After the indicator is connected to the manometer test for leaks. Accurate calibrations are dependent on good connections.

(2) Reduce the pressure until the indicator reads 40 m. p. h., read both arms of the manometer, and then the indicator.

(3) Repeat the process every 20 m. p. h. through the range of the indicator.

(4) Let air into the apparatus and in the same manner as above take reading every 20 m. p. h. *down* the scale.

(5) If it is desired to obtain the corrections for intermediate points these readings may be plotted on double logarithmic paper. First draw the ideal curve which is a straight line through the points 40 m. p. h., 5 inches; 80 m. p. h., 20 inches; 120 m. p. h., 45 inches; and 160 m. p. h., 80 inches. Then plot indicator readings as abscissas and pressures from the manometer as ordinates for "going up" and "coming down" the scale. Connect the consecutive points with straight lines, which can be distinguished from the ideal curve. To find the error at any point take the difference between the value of the abscissa on the ideal curve and the abscissa of the point on the calibration curve that has the same ordinate. If the calibration curve is to the left of the ideal the error is negative, if to the right positive. For example, in Figure V the indicator at 50 m. p. h. read too low (negative error) by 0.8 m. p. h. on the "up" calibration, and too high (positive error) by 2 m. p. h. on the "down" calibration.

(6) It will be observed that the "down" curve is to the right of the "up" curve. This is generally the case and is due to the lag. The difference in abscissas between points on the two curves having the same ordinate is the lag. Since in using an indicator it is subjected continually to increasing and decreasing pressures, both calibrations are necessary and the averages of the up and down readings may be taken as the values from which the errors are computed.

(7) A table of errors, or correction, should be posted on the instrument board beside the instrument.

In the type H air-speed indicators lag is much smaller than indicated in Figure V.

Type F indicator may be calibrated in the same manner, but a different air-speed pressure curve must be used. The values for such a curve may be computed from the following equation.

$$V = 45.2\sqrt{h}.$$

8. Clock.

In case a clock fails to keep time it should be rewound, examined, and perhaps cleaned and oiled. Before being installed again on an airplane it should be kept in the shop long enough to be regulated. But all airplane clocks in use should also be regulated after being installed, since the service conditions are so much different from the shop. For this purpose a reliable timepiece is necessary. One of the Waltham airplane clocks makes a satisfactory chronometer if wound regularly once a day and carefully handled. Its rate may be reduced to a few seconds a day and is very constant. Some means should be available for getting the exact time daily in order to rate the chronometer. If within wireless range of the Arlington Station the time signals from the Naval Observatory may be heard at

noon daily; or time signals may be received over the wire telegraph lines.

9. Other Instruments.

For the remaining standard instruments, compass and inclinometers, no directions for calibration, since no calibration of the compass is possible other than the compensation which has already been described; and no calibration of the inclinometers is necessary if this has been done correctly in the first place.

References.

Aeronautical Instruments Circular Nos. 3, 10, 11, 22, and 23, Bureau of Standards.

APPENDIX.

TOOLS FOR REPAIRING INSTRUMENTS.

Watchmaker's bench.
Watchmaker's lathe and attachments.
Staking tool.
Bench cover and material dish.
Pinion caliper.
Roller remover.
Hand remover.
Nine-hole hand tongs.
Set of cell screw-drivers.
Alcohol lamp.
Single and double eyeglass.
Oiler.
Oil cup.
Small hammer.
Flat nose pliers.
Cutting pliers.
Pin vise.
Small bench vise.
Watch brushes.
Blowpipe.
Tweezers.
Saw frame and saws.
Files.
Six and 12 inch scales.
One and 2 inch micrometers.
Spring dividers.